NUCLEARE DI QUARTA GENERAZIONE
STATO ATTUALE E PROSPETTIVE

ENERGIA NUCLEARE. STATO E PROSPETTIVE
NUCLEARE DI QUARTA GENERAZIONE
LA SOLUZIONE TECNOLOGICA ITALIANA
CONTESTO INTERNAZIONALE

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ENEA

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Outline

- Why Nuclear?!
- Why Fast Reactor?!
- Why Lead-cooled Fast Reactor?
- Italian Contributions
- International Context
- Final Remarks

Outline

- **Why Nuclear?!**
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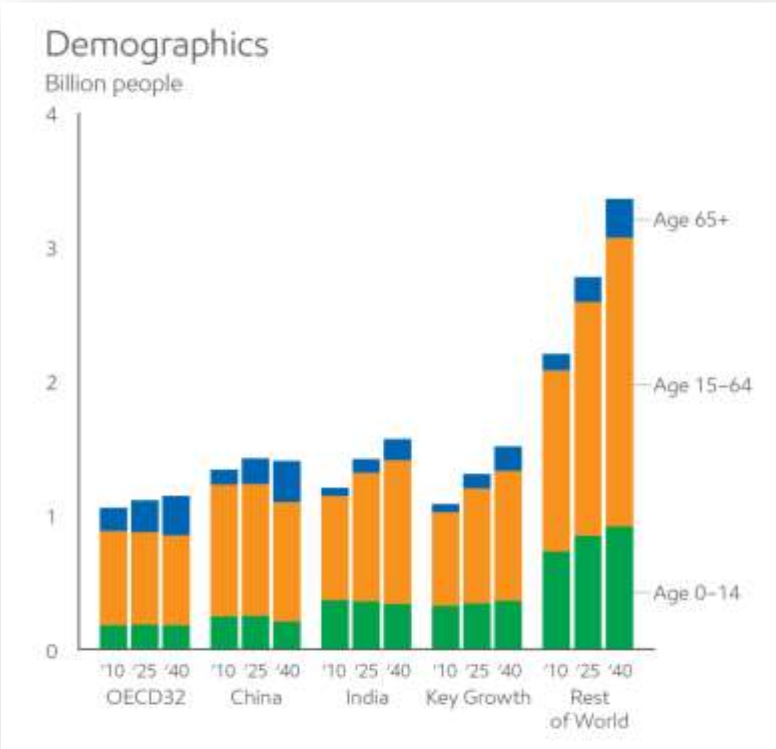
Energy Demand

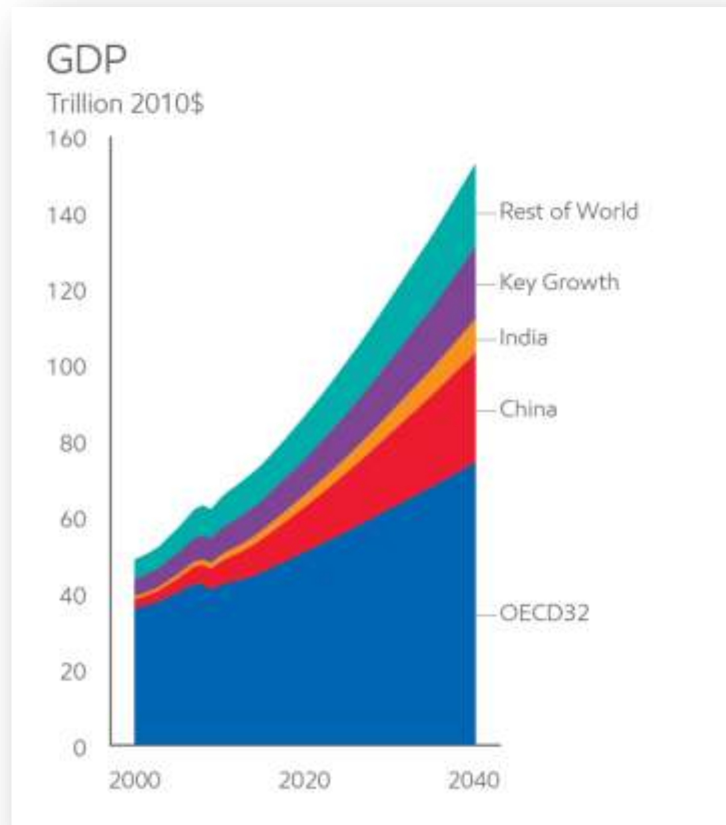
Source: Exxon Mobil Energy Outlook 2016

Energy Demand



- World population grows 25%, from 7.2 to 9 billion 2014-2040

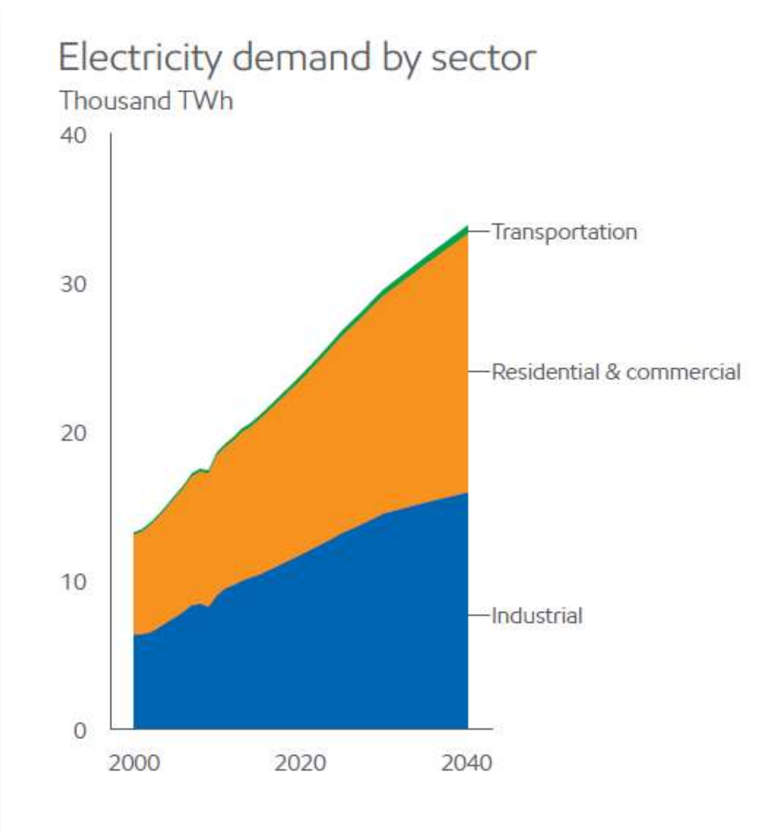
- Economic growth drives increased need for energy
- Global GDP more than doubles 2014-2040; developing countries lead growth
- China rises almost 20% of world GDP, close to US; India exceeds 5%



Source: **Exxon Mobil Energy Outlook 2016**

Electricity Demand

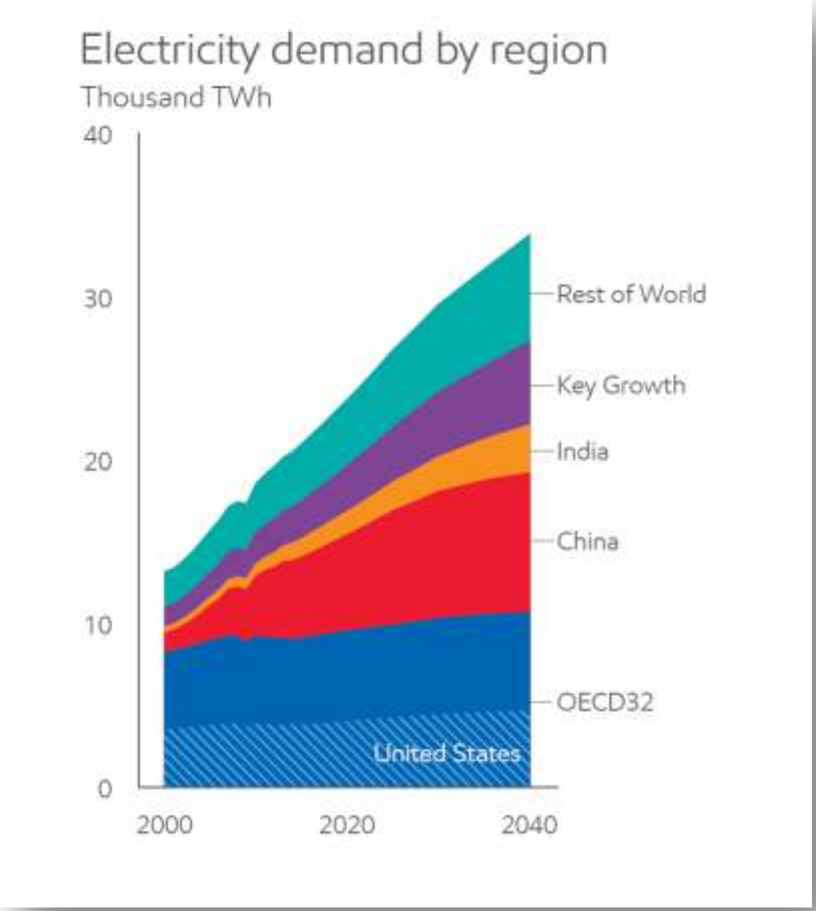
Electricity accounts for nearly all demand growth 2014-2040

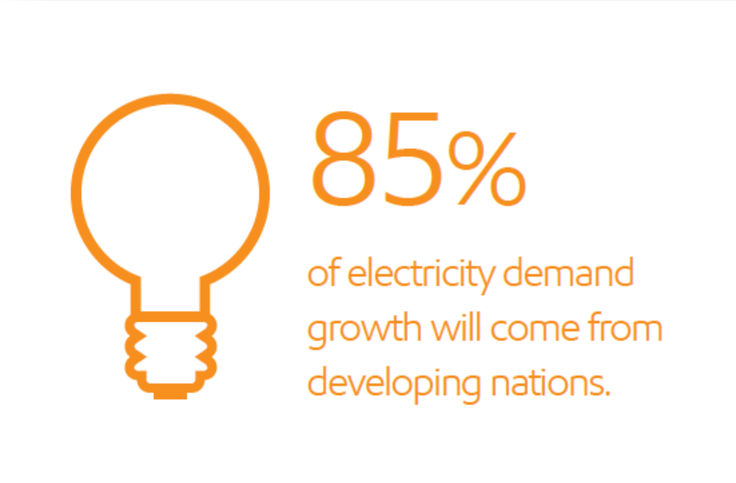


- Global electricity demand seen rising by 65% 2014-2040; 2.5 times more faster than overall energy demand
- Residential and commercial electricity demand rises 70% 2014-2040; industry up to 55%
- Industrial growth eases post-2030 as China's economy shifts from manufacturing
- Transportation electricity demand doubles 2014-2040, but only 2% of the total use

Source: Exxon Mobil Energy Outlook 2016

Electricity Demand

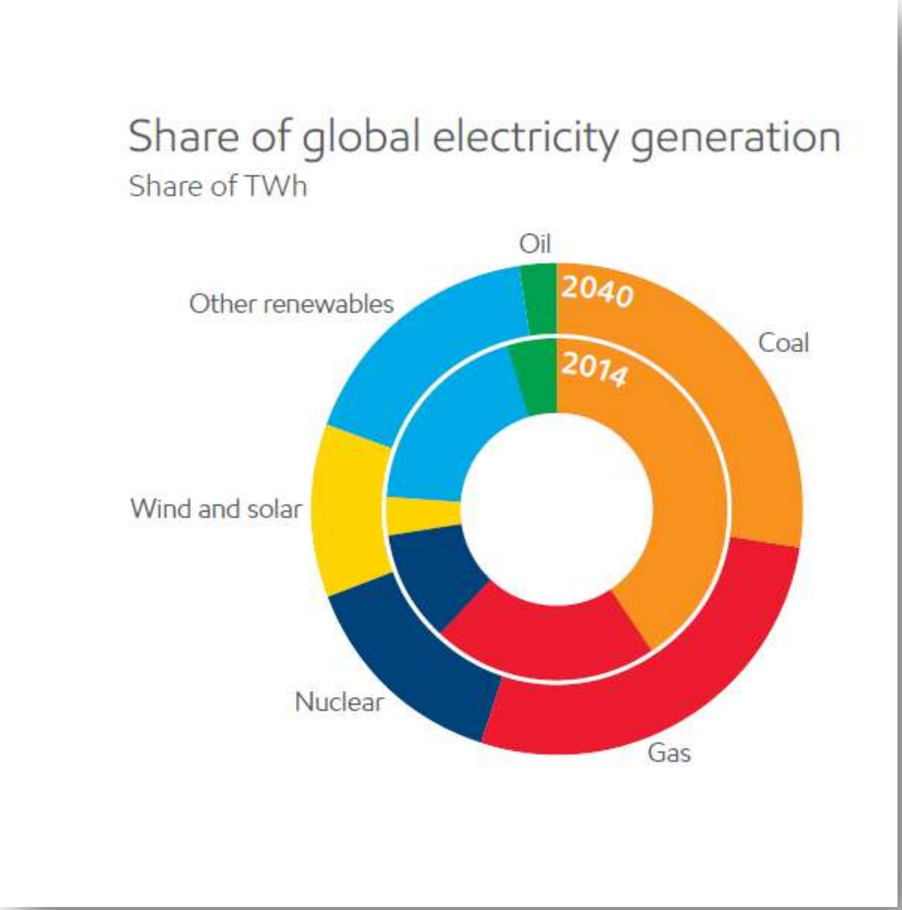




- 85% of the rise electricity demand will come from non-OECD
- China leads growth; will use one-fourth of the world's electricity by 2040
- U.S. share of global electricity demand falls from 20% to 15% 2014-2040

Source: Exxon Mobil Energy Outlook 2016

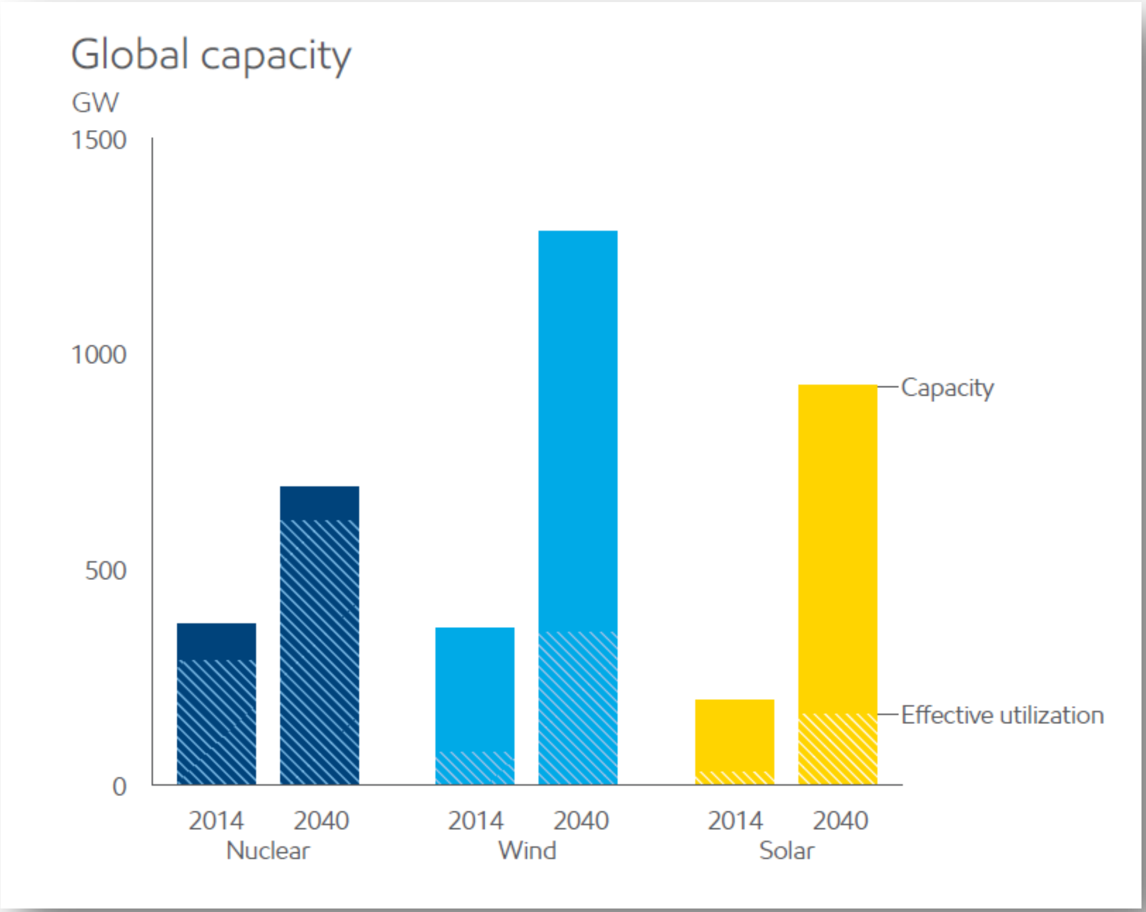
Electricity Generation



- World shifting to cleaner fuels for electricity generation, led by gas
- Coal's share shrink while natural gas, nuclear, wind solar gain
- Coal provides about 30% of world's electricity generation in 2040, versus 40% in 2014
- Wind, solar provide more than 10% of electricity by 2040, 4% in 2014

Source: Exxon Mobil Energy Outlook 2016

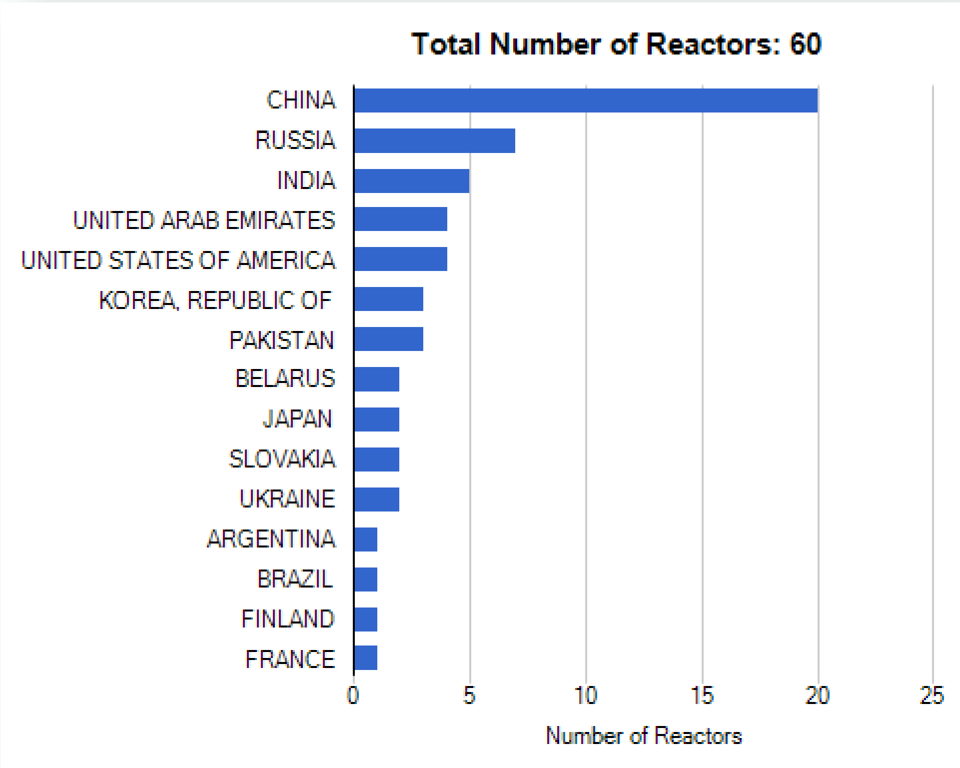
Electricity Generation & Nuclear Role

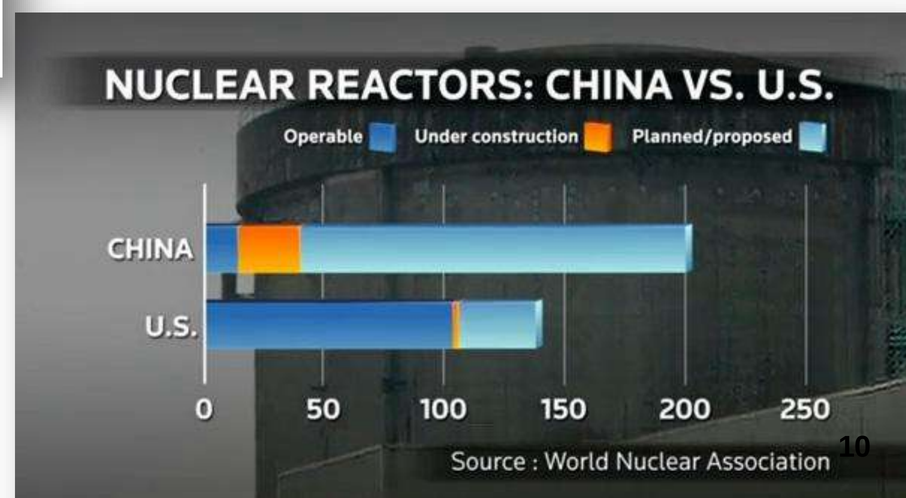


- Global nuclear, wind, solar all see big capacity additions
- Nuclear capacity to grow 85% 2014-2020, led by China
- Intermittency limits the utilization of wind, solar capacity
- Globally, less than 30% of wind capacity is utilized; solar less than 20%
- **Wind, solar provide less electricity in 2040 than nuclear despite 3 times the capacity**

Source: **Exxon Mobil Energy Outlook 2016**

Electricity Generation & Nuclear Role

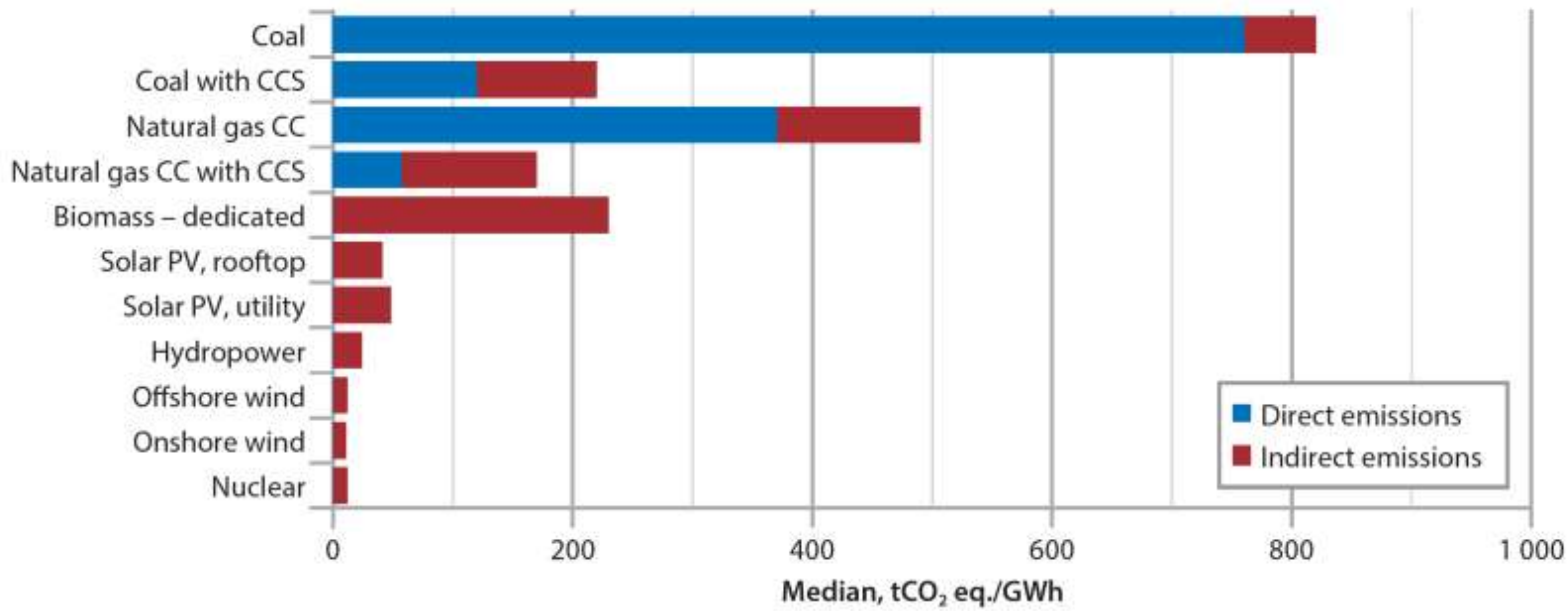




Source: IAEA-PRIS

Why Nuclear ?!

- Nuclear energy produced **11% of global electricity supply in 2013**.
- This corresponds to 18% of electricity supply in OECD countries and slightly more than 4% in non-OECD countries.
- **Nuclear is the largest low-carbon source of electricity in OECD countries**. Its share in non-OECD countries is still low but is expected to rise substantially in coming years.



Note: Lifecycle emissions from dedicated energy crops are relatively high due to the N_2O emissions from agricultural soils. N_2O has a global warming factor that is 298 times that of CO_2 (IPCC [2014], Chapter 11, p. 880).

CC = combined cycle; CCS = carbon capture and storage; GWh = Gigawatt-hour.

Source: IPCC (2014)

Why Nuclear ?! → 2DS Scenario

- The 2°C Scenario (2DS) is the main focus of Energy Technology Perspectives.

- The 2DS lays out an energy system deployment pathway and an emissions trajectory consistent with **at least a 50% chance of limiting the average global temperature increase to 2°C**.

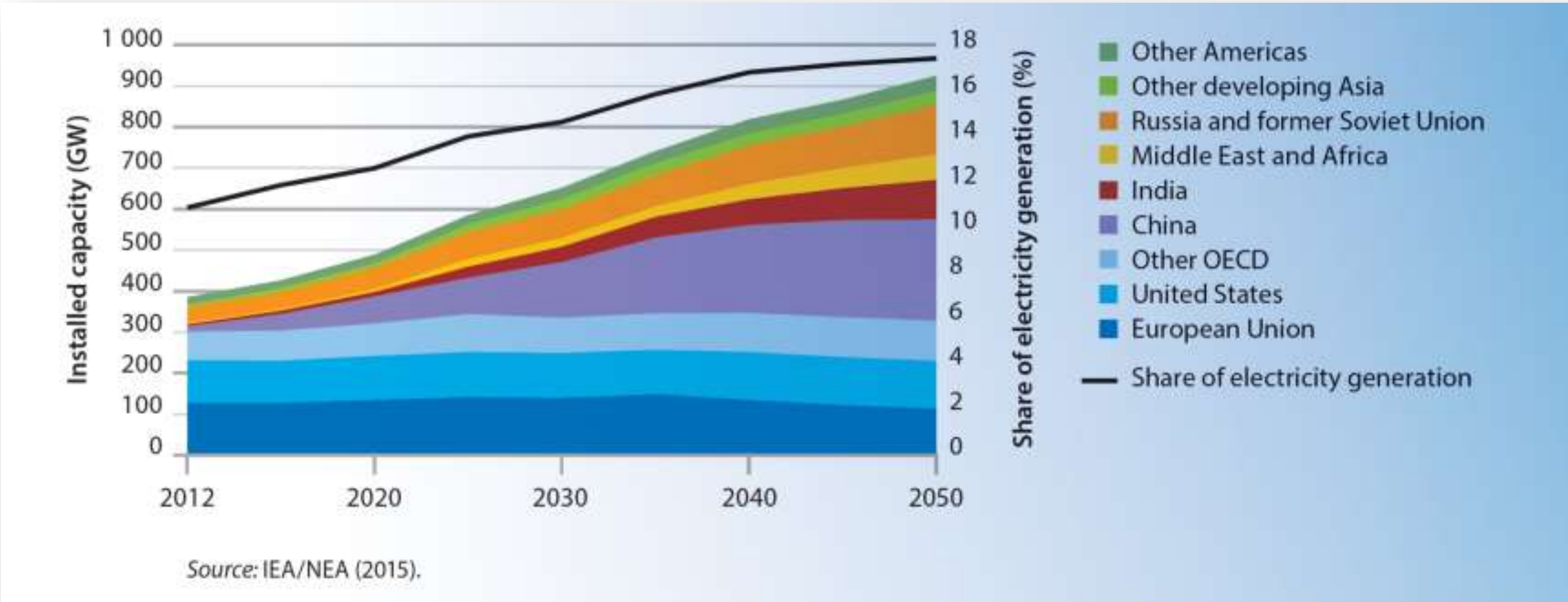
- **The 2DS limits the total remaining cumulative energy-related CO2 emissions between 2015 and 2100 to 1 000 GtCO2**.

- **The 2DS reduces CO2emissions by almost 60% by 2050 (compared with 2013), with carbon emissions being projected to decline after 2050 until carbon neutrality is reached.**

- **COP21 boosted the momentum for accelerating low-carbon technology deployment**

Source: **IEA Energy Technology Perspectives 2016**

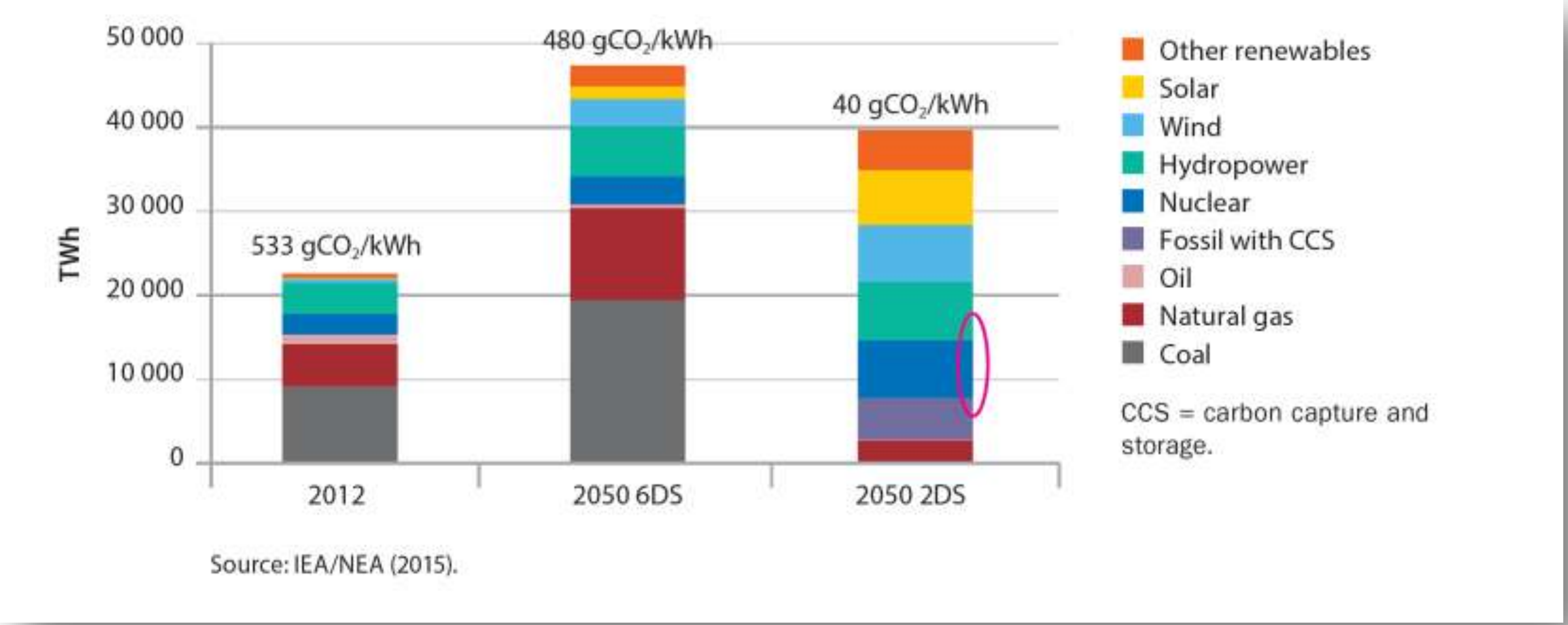
Why Nuclear ?! → 2DS Scenario



Projected nuclear capacity with regional split and share of electricity generation in the IEA *Energy Technology Perspectives* 2015 2°C scenario (2DS)

Source: **IEA Energy Technology Perspectives 2016**

Why Nuclear ?! → 2DS Scenario



Shares of different technologies in global electricity production until 2050 in the 2DS

- **cumulatively, up to 2050, nuclear power would enable the highest CO2 emission savings in comparison to other technologies**
- **in 2050, nuclear power would represent the largest source of low-carbon electricity.**

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Nuclear: Open Issues

- Nuclear Energy: good but not good enough

- Improvements
  - Safety
    - Nuclear Accidents mostly happen because of stupidity

- **Waste**
  - **Too much of it**
  - **Too long lived**

- **Economy**
  - **Once through strata uses less than 0,5% of the fuel**

Nuclear: Open Issues

waste minimisation

better use of resources

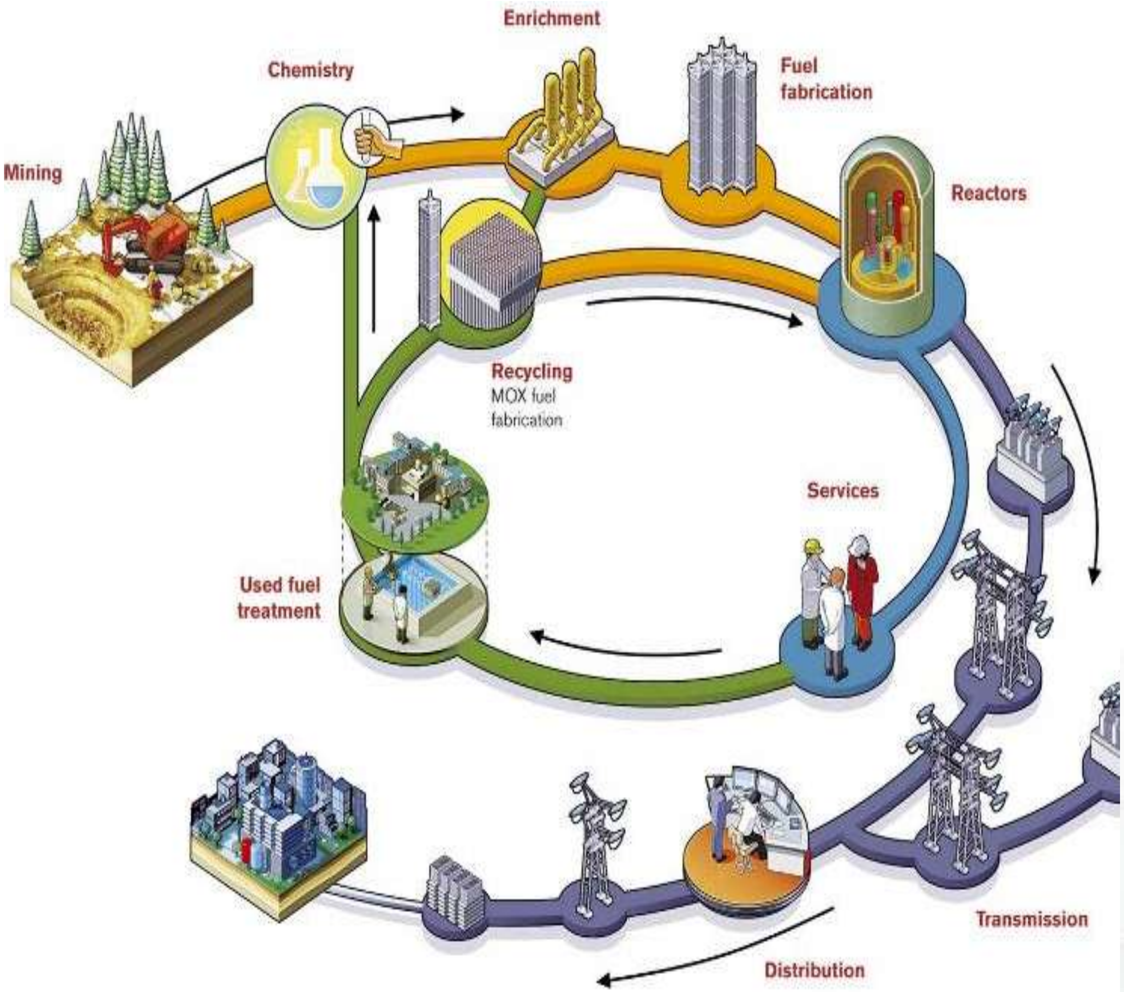
reduced proliferation risks

passive safety

Waste Minimization & Economy

The fission process used in nuclear reactors produces a number of isotopes that can be toxic to human lives and the environment.

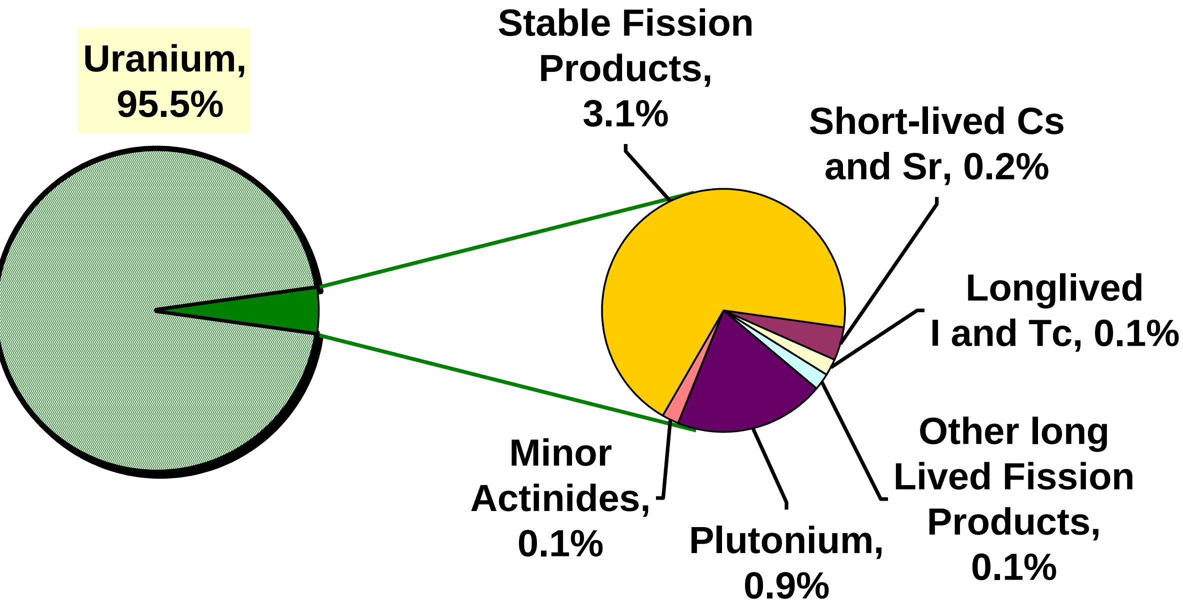
Since the start of the large scale deployment of nuclear energy, disposal of the long lived isotopes has been an issue that has had a priority in most nuclear countries.



Source: Phillip Finck and Massimo Salvatores, INL, FUNFI-2, Frascati, October 2016

Waste Minimization & Economy

Standard PWR 33GW/t, 10 yr. cooling



Most of the hazard stems from <u>Pu, MA and some LLFP</u> when released into the environment, and their disposal requires isolation in stable deep geological formations.

A measure of the hazard is provided by the radiotoxicity arising from their radioactive nature.

1 Ton of Spent Nuclear Fuel Contains:

955.4 kg U
8,5 kg Pu

<u>Minor Actinides (MAs)</u>
0,5 kg ^{237}Np
0,6 kg Am
0,02 kg Cm

<u>Long-Lived fission Products (LLFPs)</u>
0,2 kg ^{129}I
0,8 kg ^{99}Tc
0,7 kg ^{93}Zr
0,3 kg ^{135}Cs

<u>Short-Lived fission products (SLFPs)</u>
1 kg ^{137}Cs
0,7 kg ^{90}Sr

<u>Stable Isotopes</u>
10,1 kg Lanthanides
21,8 kg other stable

Source: Phillip Finck and Massimo Salvatores, INL, FUNFI-2, Frascati, October 2016

Reactor and Fuel Cycle Options to Implement P&T

The P&T objectives can be summarized as:

- Minimization of waste mass sent to a repository,
- Reduction of the potential source of radiotoxicity
- Reduction of the heat load in the repository

Strategies making use of P&T can be gathered into three categories:

- Sustainable development of nuclear energy and waste minimization (Pu as a resource)
- Reduction of MA inventory
- Reduction of TRU inventory as unloaded from LWRs

Fast neutron spectrum reactors are the most adapted technology and offer flexible options for implementation.

Source: Phillip Finck and Massimo Salvatores, INL, FUNFI-2, Frascati, October 2016

Waste Minimization & Economy

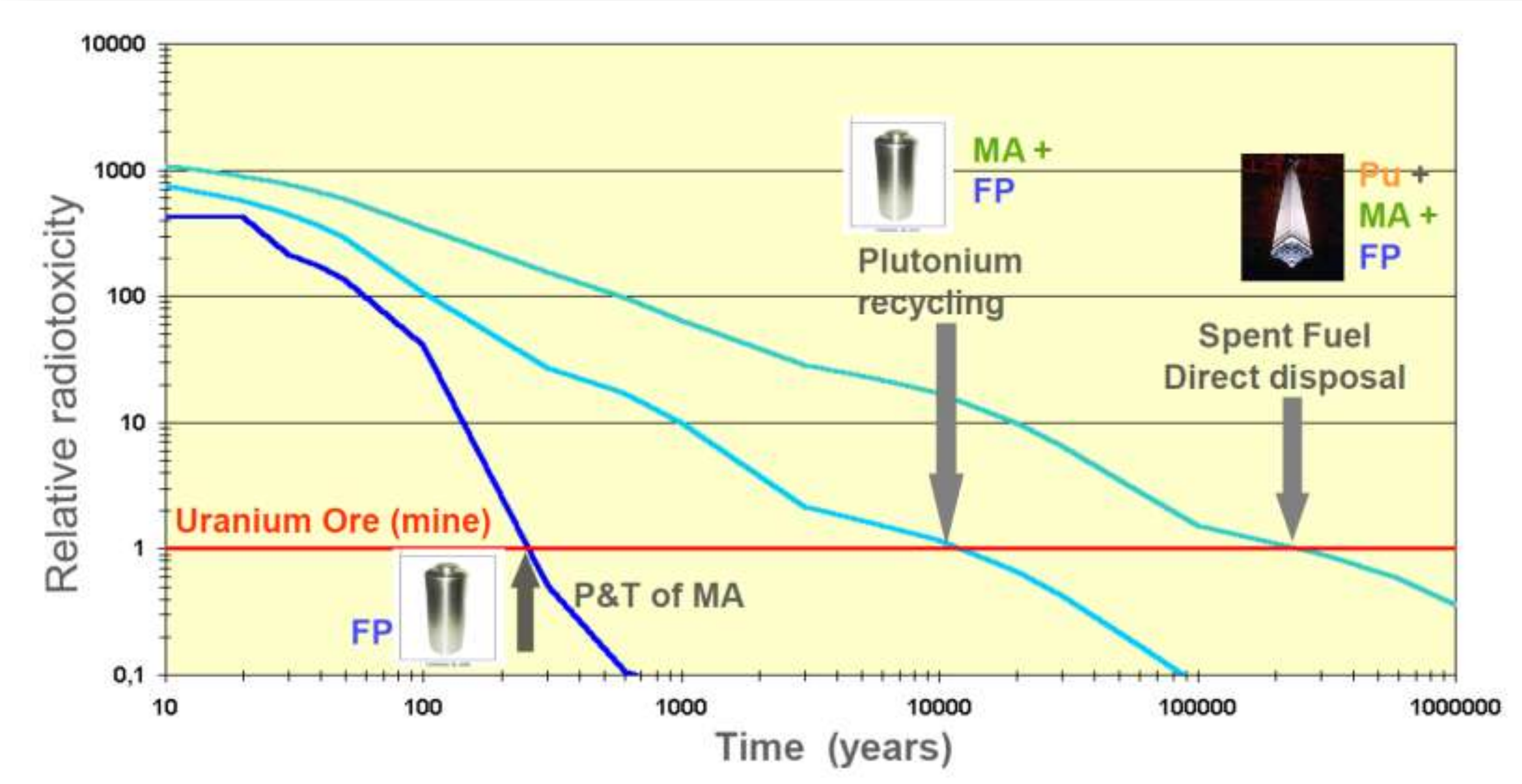
NUCLEAR MATERIALS INVENTORY (TONS) NEEDED TO PRODUCE 100TWH

		1) Present scenario	2) Near term scenario	3) Long term scenario (after 2040)
		Light water reactors	Lead –cooled fast reactors without Minor Actinides recycling.	Lead –cooled fast reactors with Minor Actinides recycling.
Natural Uranium		2100	10,8** *or* a, b, c	10,44** *or* a, b, c, d
Unused uranium, net generated Pu, Nuclear waste	Depleted Uranium from the enrichment facility.	1900 (a)	–	–
	Uranium from the spent fuel.	184 (b)	–	–
	Pu	2,6* (c)	Negligible	Negligible
	Minor Actinides (Np,Am,Cm)	0,38 (d)	0,36	Negligible
	Fission fragments	13	10,43	10,43

- * It is possible to reduce the plutonium inventory with increased production of Minor Actinides.
- ** Reprocessing losses not included

Source: L. Cinotti, "IW on Innovative Nuclear Reactors cooled by HLM: Status and Perspectives, Pisa 2012

Waste Minimization & Economy



Recycle of all actinides in spent LWR fuel in fast reactors provides a significant reduction in the time required for radiotoxicity to decrease to that of the original natural uranium ore used for the LWR fuel (i.e., man-made impact is eliminated)

From 250,000 years down to about 400 years with 0.1% actinide loss to wastes

Safety Improvement

Severe Nuclear Accidents. During the historically short period several low probability NPP accidents occurred with significant radioactivity release into environment and considerable economical losses

Three Mile Island-2
(PWR)
1979

Chernobyl-4
(RBMK)
1986

Fukushima-1
(BWR)
2011

The initial events for these accidents are of extremely low probability

technical failure | **human error** | **extreme external impact**

Safety Improvement

- Severe Nuclear Accidents occurred due to the **release of various types of potential energy accumulated in various materials**, mainly, in the main coolant.

- Radiotoxicity inventory and decay heat amount are mainly independent from the reactor type, being governed by the fission products.

- **Radiotoxicity release into environment depends strongly on the reactor type and is determined by potential (non-nuclear) energy accumulated in various materials**

    - **Coolant compression energy**
    - **Chemical energy**.

- **Potential energy is an inherent coolant property**

Safety Improvement

Coolant	Water	Sodium	Lead, Lead-bismuth
Parameters	P = 16 MPa T = 300 ºC	T = 500 ºC	T = 500 ºC
Maximal potential energy, GJ/m³, *including:*	~ 21,9	~ 10	~ 1,09
Thermal energy / *including* compression potential energy	~ 0,90 / ~ 0,15	~ 0,6 / None	~ 1,09 / None
Potential chemical energy of interaction	With zirconium ~ 11,4	With water 5,1 With air 9,3	None
Potential chemical energy of interaction of released hydrogen with air	~ 9,6	~ 4,3	None

From ICAPP 2011, Paper 11465

Effect of Potential Energy Stored in Reactor Facility Coolant on NPP Safety and Economic Parameters

G.I. Toshinsky, O.G. Komlev, I.V. Tormyshev

Safety Improvement

- Upgrading the safety level of NPPs with traditional-type reactors, (in which potential energy is stored in large amounts) requires increasing the number of safety systems and defense-in-depth barriers

- **Such measures can only reduce the probability of severe accidents** and mitigate the consequences, **but cannot eliminate them when there is large potential energy**

- Public opinion has been once more shocked by the loss of control of a nuclear plant

- Convincing demonstration that future reactors can rule out catastrophic scenarios is necessary to recover public acceptance
  - to exploit to the maximum extent solutions that can deterministically exclude scenarios which are potential initiators of accidents leading to severe core damage;
  - to consider the possibility of managing extreme events in degraded plant conditions.

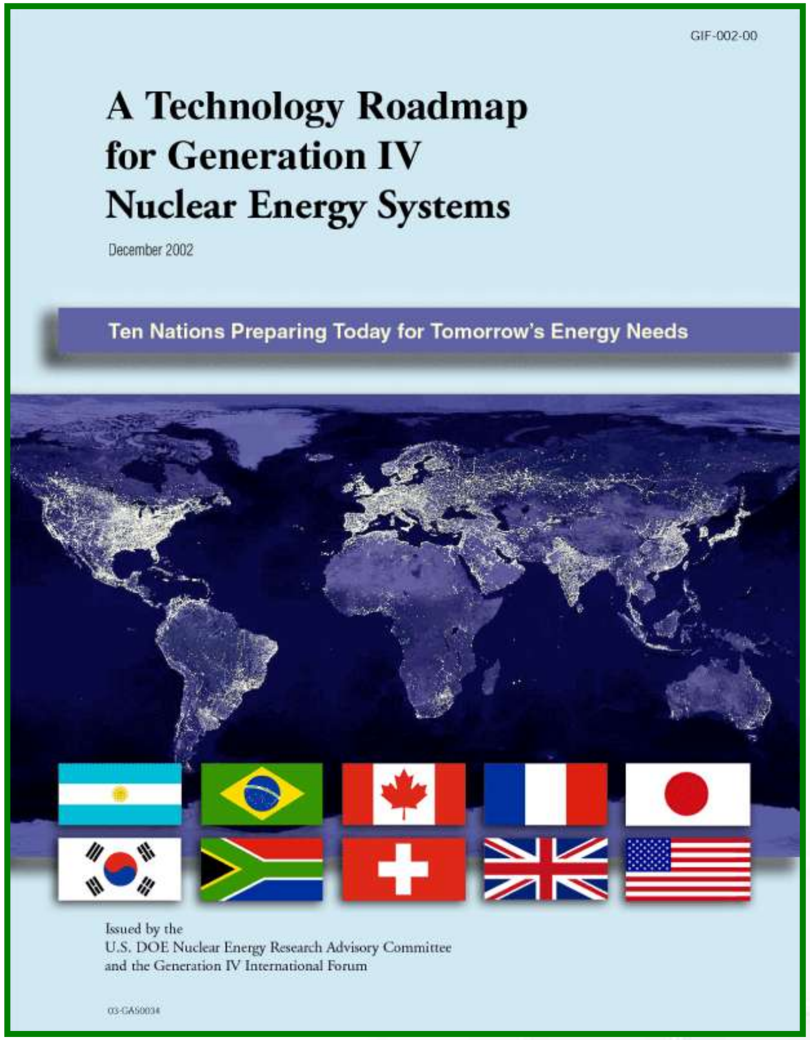
Gen. IV - International Forum Roadmap

The path from current nuclear systems to Generation IV systems is described in a 2002 Roadmap Report entitled *"A technology Roadmap for Generation IV Nuclear Energy Systems"* which:

- **defines challenging technology goals** for Generation IV nuclear energy systems in four areas:
  - ✓ **sustainability,**
  - ✓ **economics,**
  - ✓ **safety and reliability, and**
  - ✓ **proliferation resistance and physical protection.**

- **identifies six systems** known as Generation IV to enhance the future role of nuclear energy;

- **defines and plans the necessary R&D**



The GIF Systems

Generation IV Systems	Acronym
Gas-Cooled Fast Reactor	GFR
Lead-Cooled Fast Reactor	LFR
Molten Salt Reactor	MSR
Sodium-Cooled Fast Reactor	SFR
Supercritical Water-Cooled Reactor	SCWR
Very-High-Temperature Reactor	VHTR

Because the capability of fast reactors to meet the sustainability goal and hence to re-position nuclear energy from the present transition-energy role into an inexhaustible source of clean energy (akin the renewable energy sources),

- three out of the six systems selected by GIF (GFR, LFR and SFR) are fast reactors and
- for two systems (MSR and SCWR) studies have been carried out recently to explore the possibility of them to become fast reactors.

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Lead-cooled Fast Reactor

- For heavy liquid metal coolants (lead-bismuth alloy, lead) the stored thermal potential energy cannot be converted into kinetic energy.

- There is no significant release of energy and hydrogen in an events of coolant contacting with air, water, structural materials.

- There is no loss of core cooling in an event of tightness failure in the gas system of the primary circuit.

- The way to improve the NPP safety and economic performance is to implement reactor facilities with **the lowest stored potential energy**, where the inherent self-protection and passive safety properties are used to the maximal extent.

Main advantages and main drawbacks of Lead

Atomic mass	Absorption cross-section	Boiling Point (°C)	Chemical Reactivity (w/Air and Water)	Risk of Hydrogen formation	Heat transfer properties	Retention of fission products	Density (Kg/m^3) @400°C	Melting Point (°C)	Opacity	Compatibility with structural materials
207	Low	1737	Inert	No	Good	High	10580 10580	327	Yes	Corrosive

Lead-cooled Fast Reactor

How lead coolant improves the reactor design?

Lead is a low-moderating medium and has a low-absorption cross section

- Fast neutron spectrum: operation as burner of MA and improve resource utilization (Sustainability)

- Long Life Core: unattractive route for the plutonium procurement (Proliferation resistance and physical protection)

- Large fuel pin lattice (opened/closed): enhanced the passive safety (Safety and Reliability)

Lead does not interact vigorously with air or water

- Improve Simplicity and Compactness of the Plant and reduce the risk of plant damage (Economics)

- Increase the protection against acts of terrorism (Proliferation resistance and physical protection)

Lead-cooled Fast Reactor

How lead coolant improves the reactor design?

Lead has a high boiling temperature, high shielding capability and very low vapor pressure

- Un-pressurized primary system (Safety and Reliability, Economics)
- Enhancements in passive safety (Safety and Reliability)

Lead has a high heat transfer, specific heat, and thermal expansion coefficients

- Decay heat removal by natural circulation (Safety and Reliability)

Lead has a density close to that of fuel, and retains fission products

- Reduce the risk of re-criticality and vessel damage in the case of core melt (Safety and Reliability)
- No need of off-site emergency response (Safety and Reliability)

A comprehensive R&D program is necessary because of:

- **The use of a new coolant and associated technology, properties, neutronic characteristics, and compatibility with structural materials of the primary system and of the core.**

- **Innovations which require validation programs of new components and systems (the SG and its integration inside the reactor vessel, the extended stem fuel element, the dip coolers of the safety-related DHR system, pump, OCS, …)**

- **The use of advanced fuels (*at least in a further stage*).**

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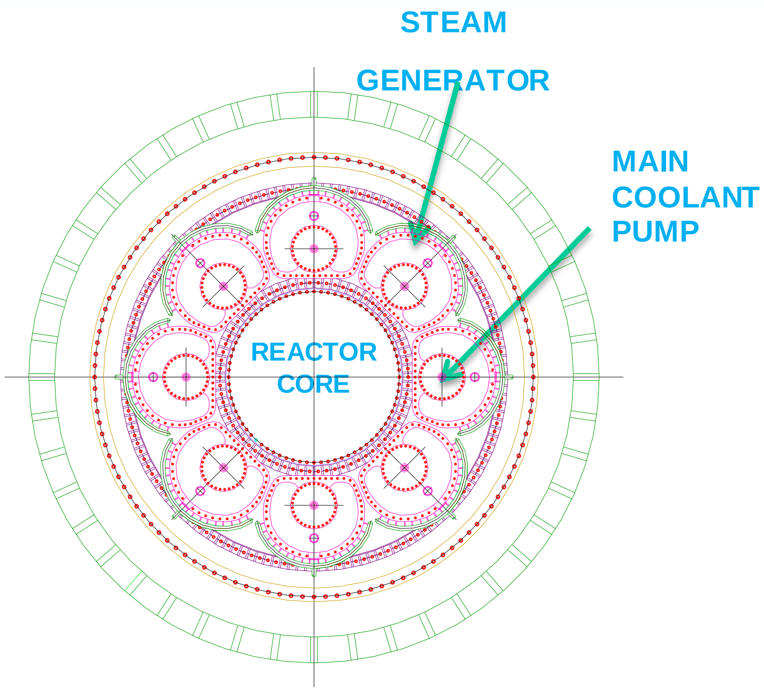
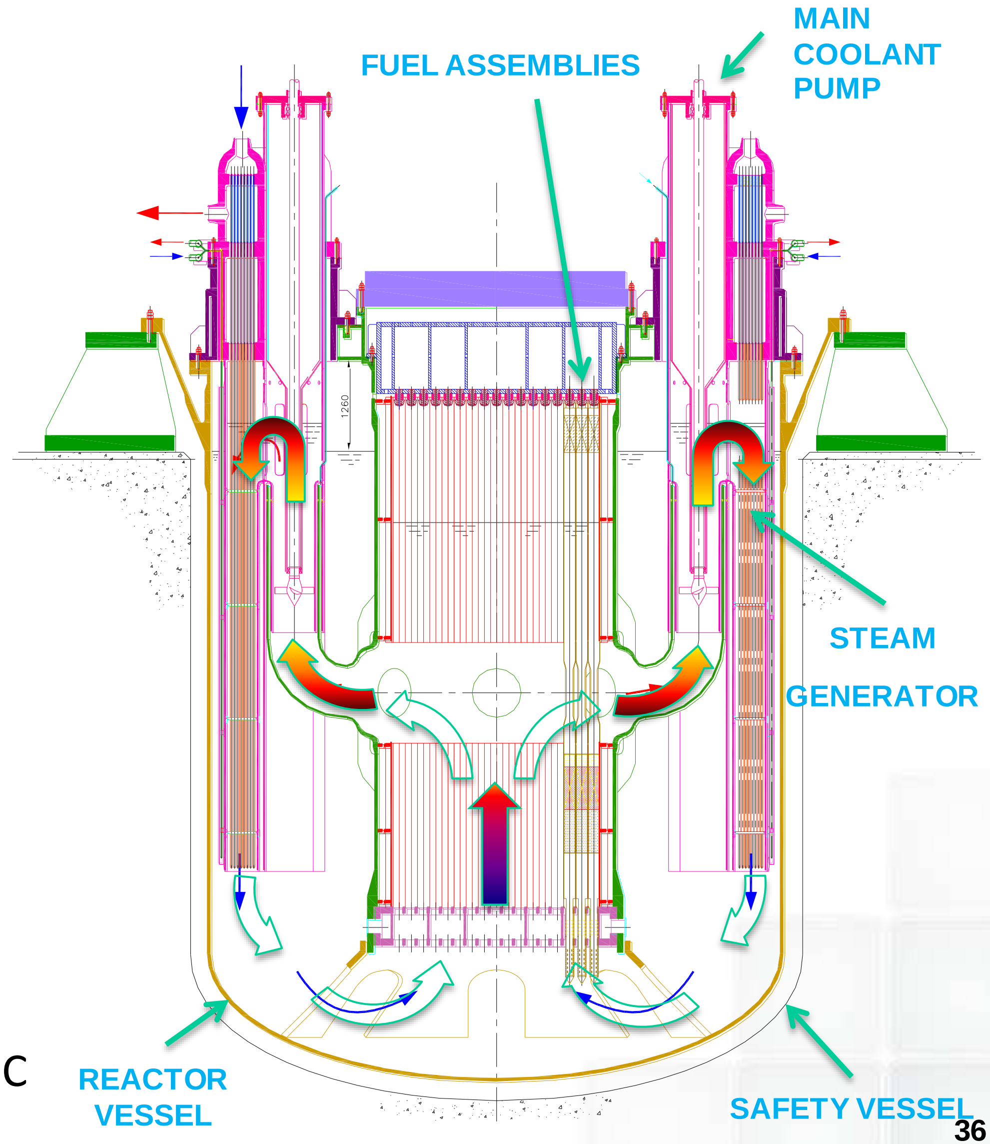
Italian Contribution





- *Power*
  300 MWth (125 MWe)
- *Primary cycle*
  Molten Lead 400-480 C
- *Secondary cycle*
  Water/superheated steam:335-450 C

Italian Contribution

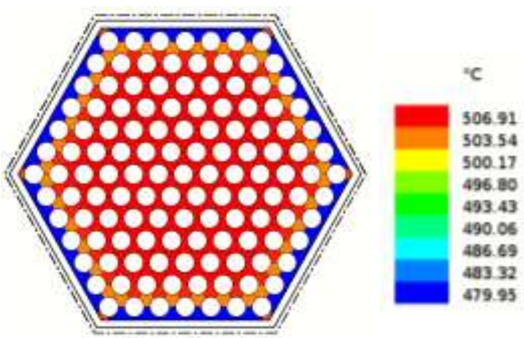
Framework Agreement (AdP) between the Italian Ministry for Economic Development (MiSE) and ENEA.

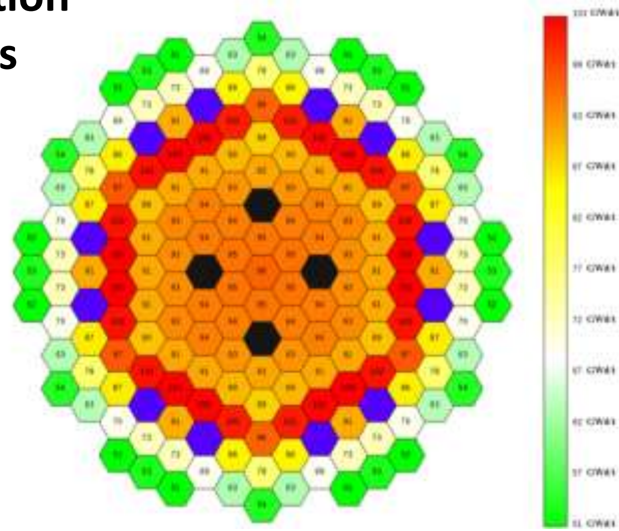
- ❑ **Project B.3.1 → Nuclear Fission**
  - ❑ **LP2 "International Collaboration on Gen-IV Nuclear Systems"**

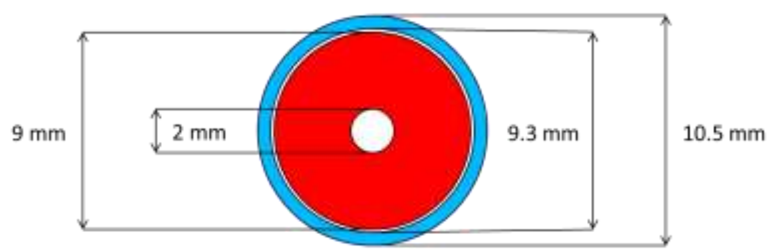
- ❑ **Design and Safety Analysis**
- ❑ **Structural Materials and Coolant Chemistry**
- ❑ **Thermal-Hydraulic**

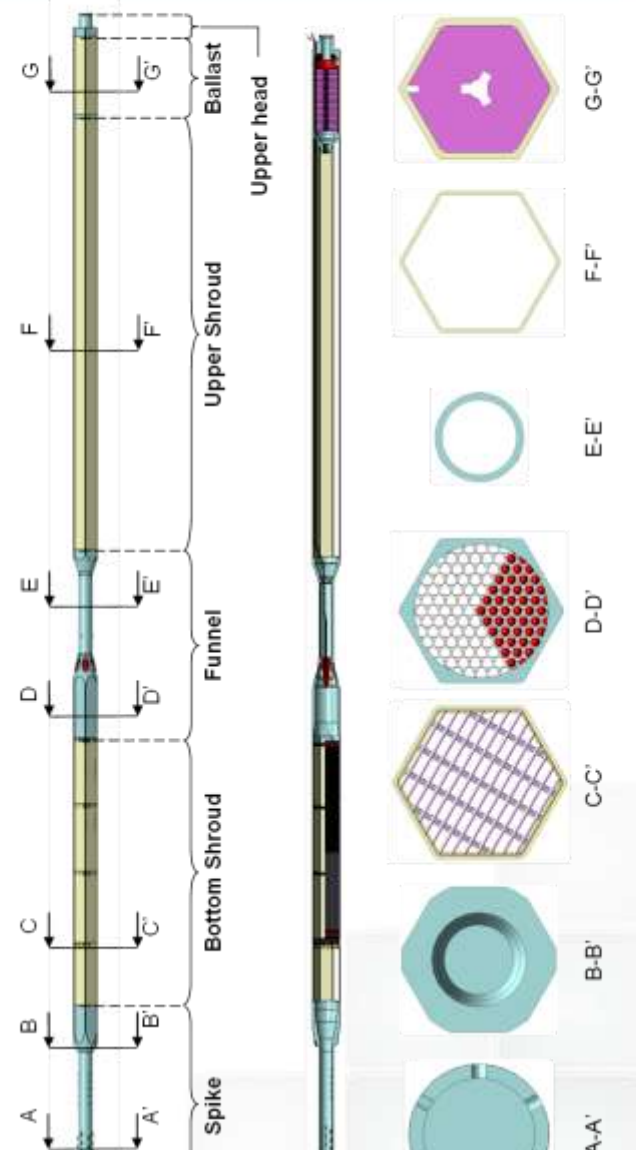
Reactor Core Design

- Fuel Pin
- Fuel Assembly & Fuel Pin Bundle
- Core Map
- Control Rod & Safety Rod
- Refueling Strategy & Burnup Performance
- Reactivity Feedback Coefficients
- Uncertainties propagation
- V&V of neutronic codes



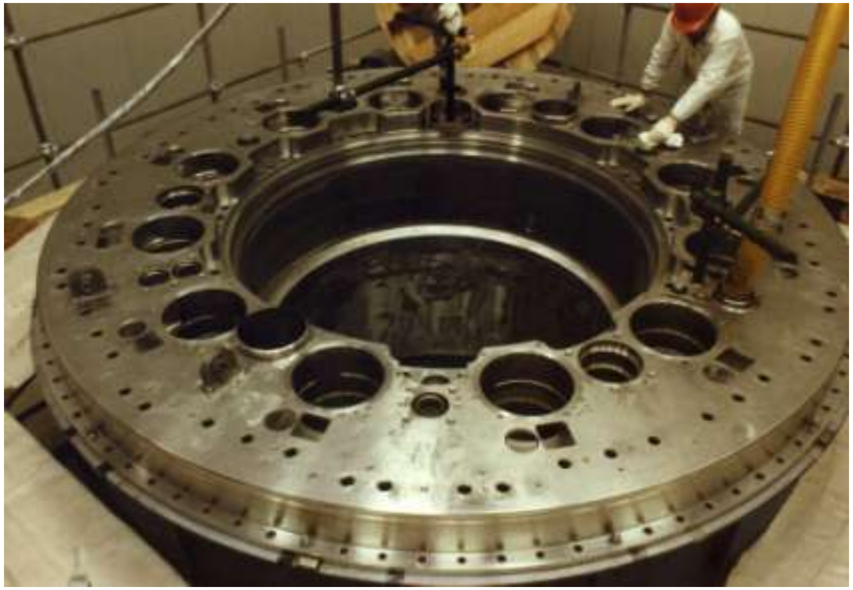


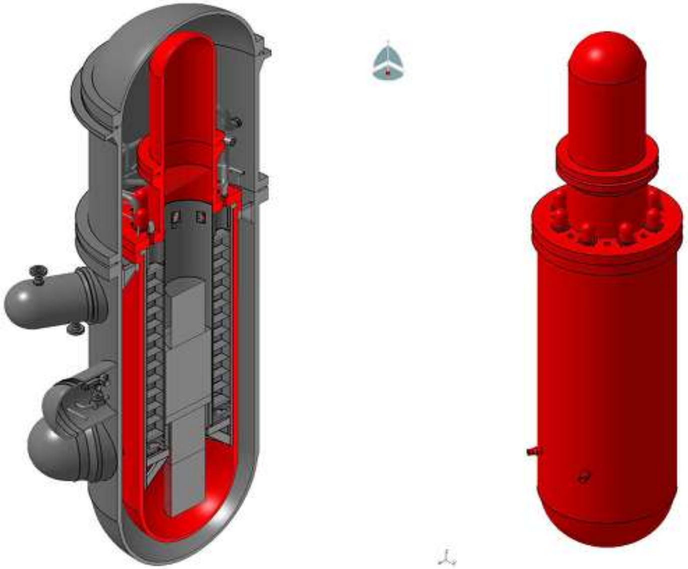




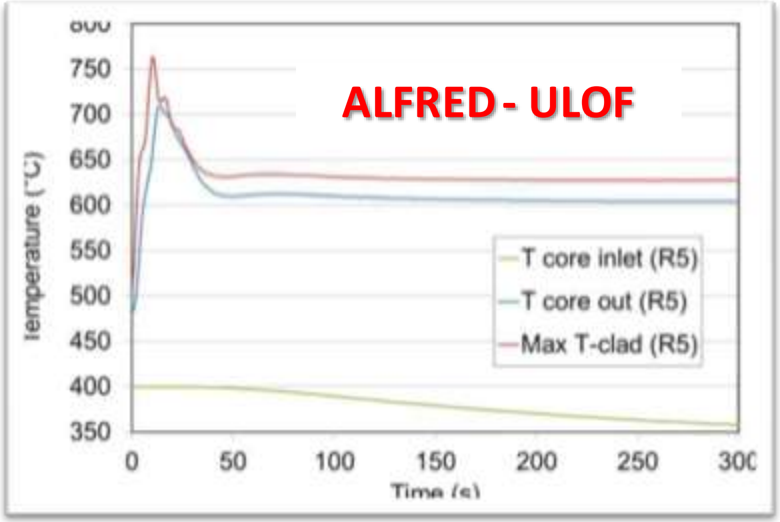
Nuclear System Design

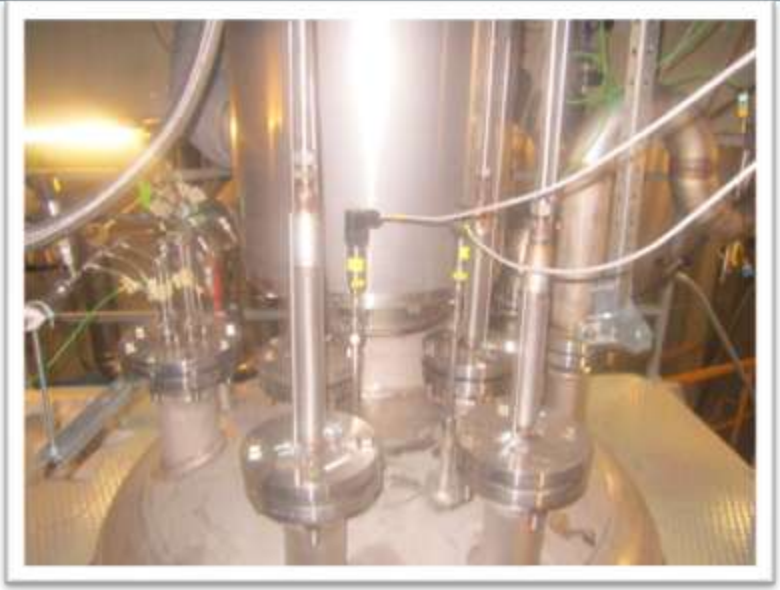
- Primary System Design and Integration
- Design according to Nuclear Rules (ASME)
- Seismic (& Sloshing) Analysis

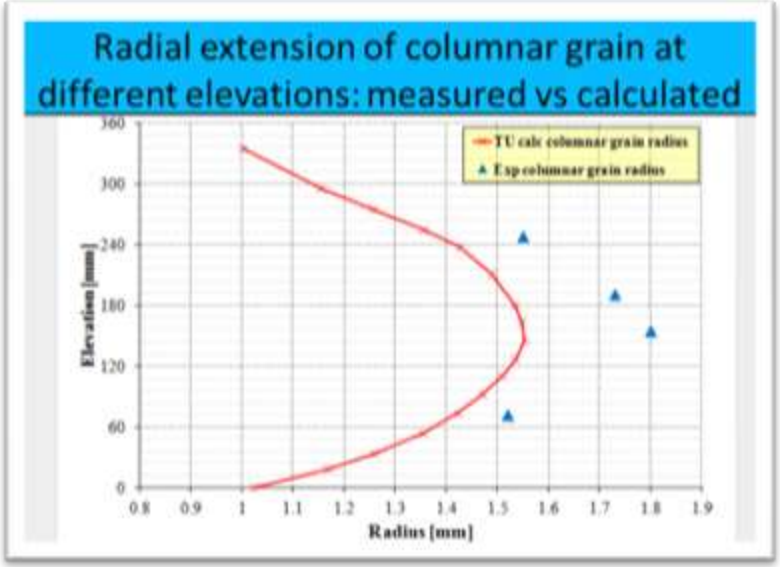


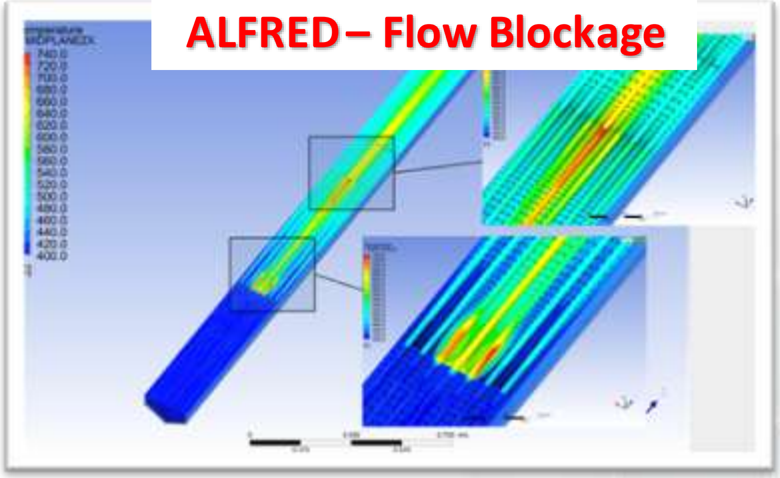


Safety Analysis









Industrial Supply Chain Identification

- The **reliance on a robust global supply chain can have significant implications to schedule and cost overruns**.
- It is important that all parties involved in nuclear construction understand these risks and are able to identify the unique supply chain challenges and opportunities.
- In doing so, improvement initiatives and loss prevention measures can be implemented at the earliest opportunity helping to maximise supply chain efficiency whilst minimising risk.

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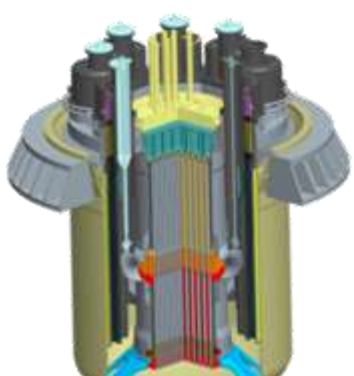
International Context

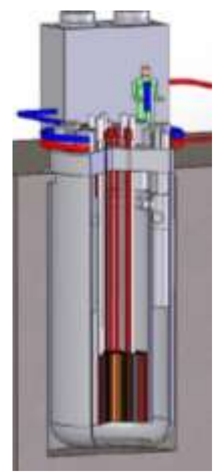
- **SNETP → Sustainable Nuclear Energy Technological Platform**
  - To ensure the long-term sustainability of nuclear energy, **Gen IV Fast Neutron Reactors should be available for deployment by 2040** or even earlier. Therefore an ambitious yet realistic R&D and demonstration programme is to be put in place.
  - **ESNII → European Sustainable Nuclear Industrial Initiative**
    - **ESNII addresses the need for demonstration of Generation IV Fast Neutron Reactor technologies, together with supporting research infrastructures, fuel facilities and R&D work.**
    - **The main goal of ESNII is to design, license, construct, commission and put into operation before 2025 the Sodium Fast Reactor (SFR) Prototype reactor called ASTRID and the flexible fast spectrum irradiation facility MYRRHA.**

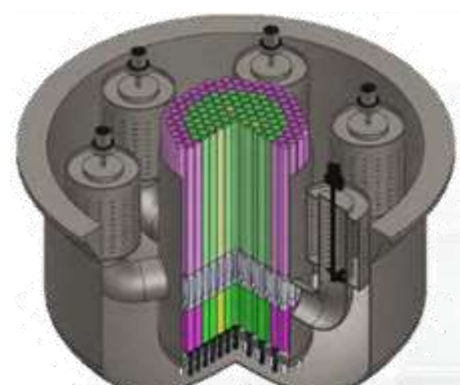
- **SRIA → Strategic Research and Innovative Agenda (2013)**
  - "……**Lead Fast Reactor technology has significantly extended its technological base and can be considered as the shorter-term alternative** technology, whereas the **Gas Fast reactor technology has to be considered as a longer-term alternative option.**

International Context

- 2015 - Republic of Korea joined the GIF LFR Steering Committee
- CooA on LFR technology and Safety between LEADER Consortium and ROSATOM-NIKIET (BREST-OD-300 construction during 2016-17)
- SEALER project by LeadCold (spin-off from KTH) funded by VINNOVA, and now by KIC InnoEnergy
- Application to DOE FOA by Westinghouse (proposal based on LFR concept) – looking at opportunities in Europe







FALCON Consortium

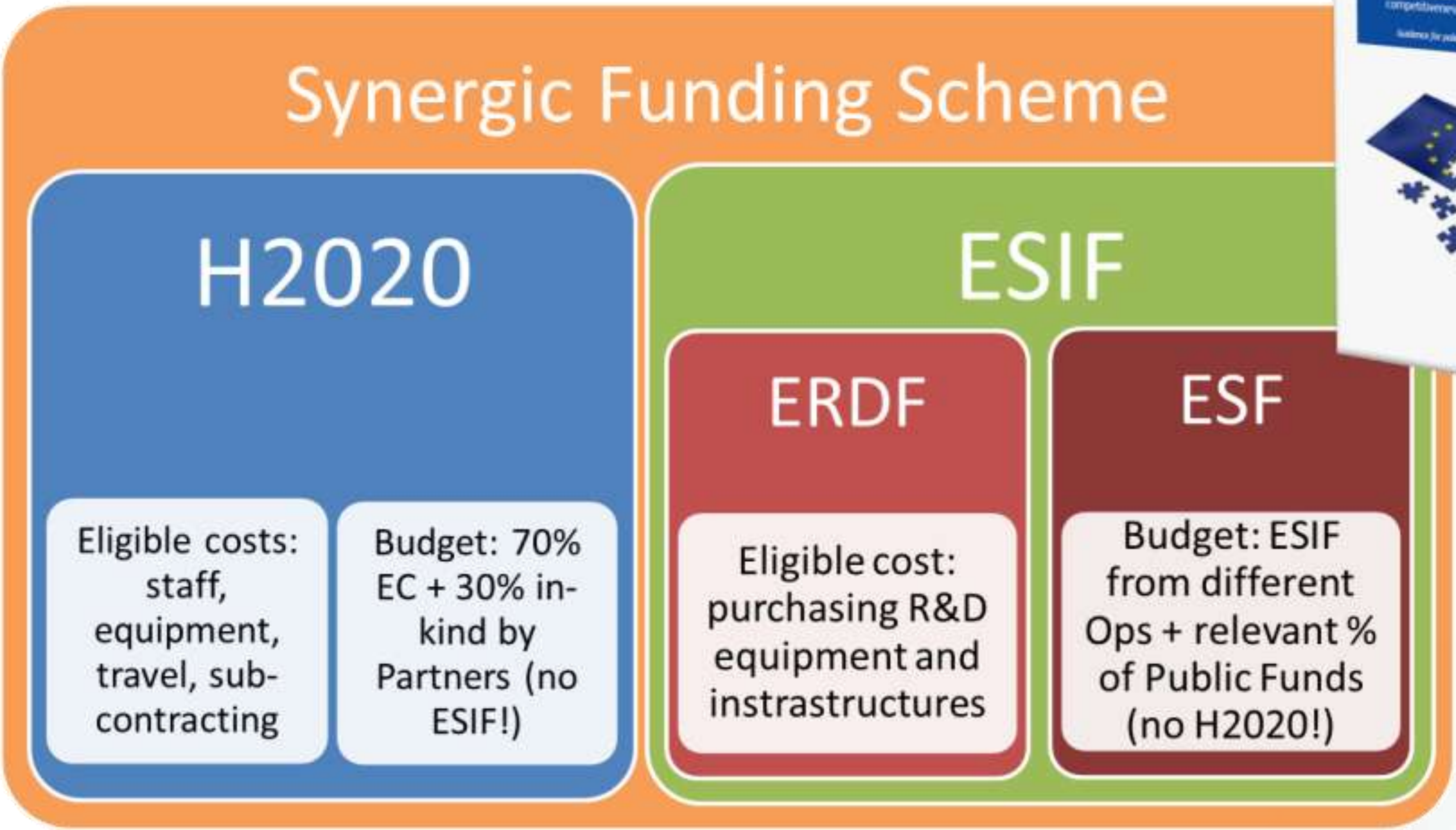
PHASE 1

- Unincorporated consortium
- In-kind contributions
- Optimize the cooperation
- Areas: strategic, management, governance, financial and technical

PHASE 2

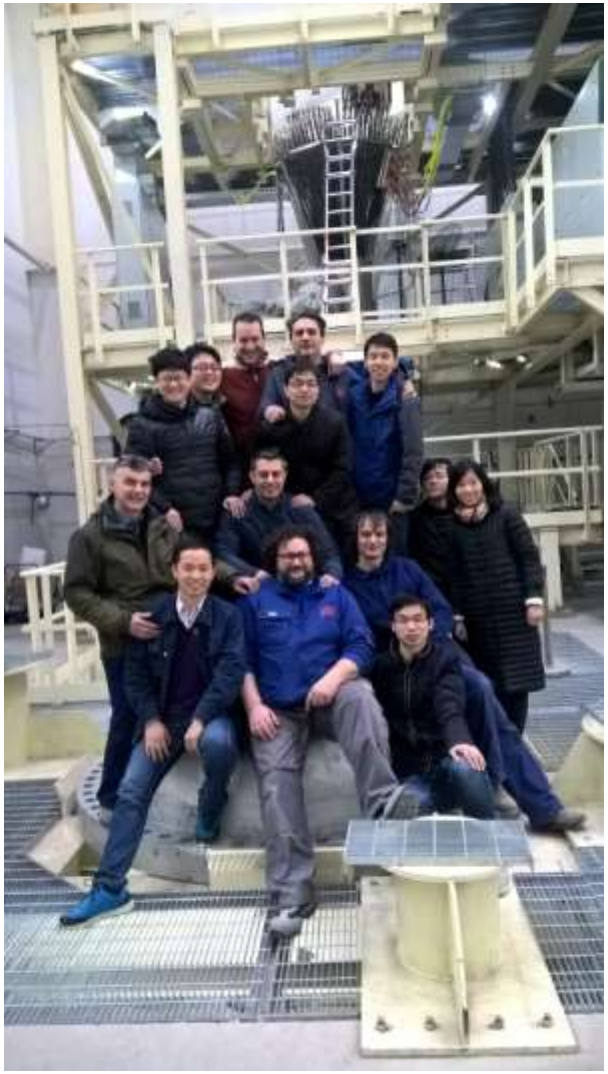
- Detailed agreement
- Manage the R&D needs
- Engineering design
- Licensing, and
- Commit the construction

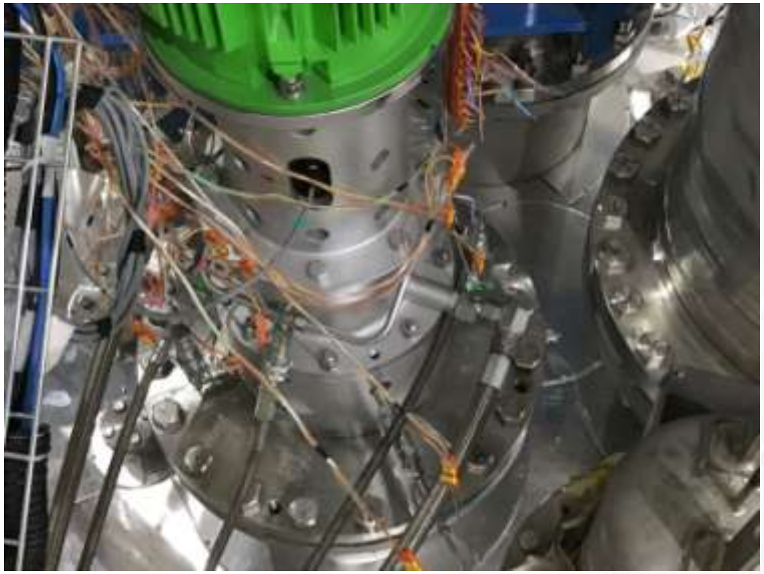
Exploiting Potential Synergies in Funds



International Context

China (CASHIPS-INEST)





Outline

- Why Nuclear?!
- Why Fast Reactor?!
- Why Lead-cooled Fast Reactor?
- Italian Contributions
- International Context
- **Final Remarks**

Final Remarks

- Nuclear will play still an important roles in the next years.

- Nuclear energy technology **is among the most reliable and safer technologies**.
  Nevertheless a in improvement is required about:
    - **Safety**
    - **Waste**
    - **Economy**

- Gen-IV reactors have been conceived to match these goals. Among the others, **Lead cooled Fast Reactors** seems to be the most promising! (but R&D needs are not negligible…)

- In this context the **Italian contribution is significant worldwide**. ENEA and its industrial partners led the technology development.

- International Context is positive (everyday more!!)

"At first you could hear the sound of the neutron counter, clickety-clack, clickety-clack. Then the clicks came more and more rapidly, and after a while they began to merge into a roar; the counter couldn't follow anymore (...)

Again and again, the scale of the recorder had to be changed to accommodate the neutron intensity which was increasing more and more rapidly. Suddenly, Fermi raised his hand. 'The pile has gone critical', he announced. No one present had any doubt of it."